Ministry of Science and Higher Education of the Russian Federation

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)

ESSAY

MIRROR WORLD

$m_p - m_e < m_n < m_p$

Student: M. A. Rakhimova
Group: M21-115
Professor: M. Yu. Khlopov

Moscow 2023

Contents

1 Introduction

In 1956, the paper "Question of Parity Conservation in Weak Interactions"by Lee and Yang was published. [1], which addressed the violation of P-accountability in weak interactions and proposed ideas for experiments to detect this effect.

One idea was to measure the angular distribution of electrons escaping from the β-decay of polarized nuclei. In 1957 a corresponding experiment was carried out [2]. It was obtained that the mirror reflection of this process leads to a process with the opposite polarized nuclei in the preferred direction of electron escape, which confirmed the violation of the P-count.

In addition, Lee and Young in [1] considered the theoretical problem arising from the P-violation — the non-equivalence of left- and right-oriented coordinate systems.

This problem was that the P-transformation of the violating P-account process led to a process that did not exist in nature. To restore equivalence, Lee and Young put forward the theory of the existence of mirror partners of particles. Such an assumption meant the mutual substitution of ordinary particles and their mirror partners in the P-transformation.

On the basis of the theory proposed by Landau, Lee et al. on the strict conservation of CP-accountability, antiparticles were put forward for the role of mirror partners. However, this assumption was disproved by the experimental detection of CP-violation in decays of K^0-mesons [3].

In 1966 I. Yu. Kobzarev, L. B. Okun and I. Ya. Pomeranchuk showed that mirror particles cannot interact with ordinary world particles through strong and electroweak interactions. Besides the gravitational interaction between ordinary and mirror particles, there are other possibilities, such as mixing of ordinary and mirror photons [4], the transition between the ordinary left and the mirror right neutrino [5], etc.

2 The physical properties of the mirror world with $m_p - m_e < m_n < m_p$

In the present paper it is assumed that the mechanisms of generation of baryonic excess in the ordinary and mirror worlds are equivalent. In such case, due to the fact that the SR disturbing effects of the mirror partners should have the opposite sign to the ordinary ones, there should be an excess of mirror antiparticles in comparison with the mirror particles. However, due to absence of electrically weak and strong interactions between mirror and ordinary particles in this model there is a freedom to choose a sign of the baryon number [6]. Then we can stipulate that in the mirror world there is also an excess of baryons with respect to antibaryons.

The model under consideration assumes the following ratio of baryon masses:

$$m_p - m_e < m_n < m_p$$

Since the neutron in this model is the lightest, its decay is forbidden by the law of conservation of energy. Let's also consider the decay of the proton:

$$p \to n + e^+ + \nu$$

Such a process is also impossible due to the mass ratio: $m_p < m_e + m_n$.

Thus, in the considered model, both the neutron and the proton are stable particles.

The properties of the other particles of the Standard Model (SM) of the ordinary world in this model are assumed to be the same. In this model it is assumed that inflation and baryosynthesis took place identically in the ordinary and mirror worlds, their difference will become essential at the stage of nucleosynthesis.

The question of mirror neutrinos is beyond the scope of this paper and will be discussed later.

3 Model influence on cosmological processes

3.1 Inflation and bariosynthesis

The presence of mirror matter by itself does not solve the problems of the old hot Universe scenario. Thus, it is necessary to make additional assumptions about cosmological processes and evaluate the influence of the model on their course.

As a model of inflation we will accept the model of chaotic inflation [7], assuming the possibility of different amplitudes of ordinary and mirror inflatons. This assumption leads to a domain structure in the distribution of ordinary and mirror matter [8].

We will assume symmetry of initial conditions for ordinary and mirror particles. Thus we obtain that except for regions of very large mirror domains the relativistic mirror and ordinary particles are present in equal quantities and have the same temperature. So, in the early Universe it is necessary to take into account the contribution from both kinds of matter to the total density.

At the initial stages of development of the Universe, by analogy with the ordinary world, an excess of mirror quarks over antiquarks is assumed. Thus, after the mirror KCD phase transition some number of excess mirror nucleons are formed, forming mirror matter.

Let's evaluate the effect of the presence of mirror matter on the quenching temperature, at which the thermodynamic equilibrium between neutrons and protons is violated.

The thermodynamic equilibrium is broken at the moment when the characteristic weak interaction time τ becomes larger than the cosmological time t. This corresponds to the moment when the rate of expansion of the Universe begins to exceed the rate of weak interaction processes.

The characteristic weak interaction time can be calculated as follows:

$$\tau = \frac{1}{n\sigma v}, \tag{1}$$

where n is the concentration of electron-positron pairs, σv is the rate of their interaction with neutrinos.

At the RD stage, the concentration of electron-positron pairs as a function of temperature is determined by the expression:

$$n = \frac{4\zeta(3)T^3}{\pi^2} \tag{2}$$

Weak interaction cross section:

$$\sigma \sim G_F^2 T^2, \tag{3}$$

G_F is Fermi contant.

The rate of expansion of the universe:

$$H \sim \frac{\sqrt{g_*}T^2}{m_{Pl}}, \tag{4}$$

g_* is the number of ultrarelativistic degrees of freedom.

The number of ultrarelativistic degrees of freedom:

$$g_* = 2 + \frac{7}{8} \cdot 4 + \frac{7}{8} \cdot 2 \cdot 3 = \frac{43}{4} \tag{5}$$

Using the formulas (1)-(5), we come to the dependence of the quenching temperature on the number of ultrarelativistic degrees of freedom:

$$T \sim \frac{g_*^{\frac{1}{6}}}{(G_F^2 m_{Pl})^{\frac{1}{3}}} \tag{6}$$

Substituting the numerical values, we obtain an estimate of the quenching temperature $T \sim 1$ MeV. Substituting this value into the Saha equation, we can obtain the ratio of the number of neutrons to the number of protons at the moment of quenching.

$$\frac{n_n}{n_p} = \left(\frac{m_n}{m_p}\right)^{\frac{3}{2}} \exp\left(-\frac{m_n - m_p}{T}\right) \tag{7}$$

Let's take into account the restrictions arising from the mass ratio on the proton-neutron mass difference:

$$0 < m_p - m_n < 0.5 \text{ MeV} \tag{8}$$

$$\left(\frac{m_n}{m_p}\right)^{\frac{3}{2}} \approx 1 \tag{9}$$

Thus we obtain the range of admissible values of the ratio of the number of neutrons to the number of protons:

$$1 < \frac{n_n}{n_p} < 1.65 \tag{10}$$

The obtained result suggests that within the considered model there will be an excess of mirror neutrons. It is also important to remember here that both protons and neutrons in the model are stable, so this ratio will not change in the future.

3.2 Nucleosynthesis

During nucleosynthesis, fusion reactions of neutrons with protons first produce deuterium nuclei:

$$n + p \to D + \gamma$$

Further reactions of heavier nuclei formation take place:

$$n + D \to T + \gamma$$

$$D + D \to T + p$$

$$T + D \to {}^4He + n$$

$$T + p \to {}^4He + \gamma$$

$$p + D \to {}^3He + \gamma$$

$$D + D \to {}^3He + n$$

$$T + {}^4He \to {}^7Li + \gamma$$

Let's determine the primary chemical composition of the mirror substance. The mass fraction of helium can be estimated by the following formula:

$$X_{He} = \frac{m_{He} \cdot n_{He}}{m_p(n_p + n_n)} \tag{11}$$

$$\frac{m_{He}}{m_p} \approx 4 \tag{12}$$

Since protons and neutrons are stable in this model, their concentrations do not change with time. Due to the high formation rate of deuterium and helium, let's assume that almost all protons have transferred to ^4He.

$$n_{He} = 0.5 n_p \tag{13}$$

$$X_{He} = \frac{2}{\frac{n_n}{n_p} + 1} \tag{14}$$

Where we get that $0.75 < X_{He} < 1$.

The mass fraction of free neutrons can be calculated as follows:

$$X_n = \frac{n_n - n_p}{n_n + n_p} \tag{15}$$

Thus, we obtain that $0 < X_n < 0.25$

The absence of stable nuclear states with atomic number A = 5 creates an almost impassable barrier to further nuclear transformations of primary nucleosynthesis Thus, the primary chemical composition of mirror matter is mostly stable neutrons and helium nuclei.

However, since the universe is expanding, not all protons could be captured by deuterium nuclei with the subsequent formation of helium. Let's estimate the concentration of free protons. To do this, let's first find the temperature at which nucleosynthesis occurs. It can be estimated from the following relation:

$$X_D(T_{NS}) \approx \eta_B \left(\frac{2.5 T_{NS}}{m_p}\right)^{\frac{3}{2}} e^{\frac{\Delta_D}{T_{NS}}} \sim 1, \tag{16}$$

where $\eta_B \sim 10^{-9}$ is the baryon-photon ratio;

$\Delta_D = 2$ MeV is the binding energy of deuterium.

By substituting numerical values, we obtain an estimate:

$$T_{NS} \approx 60\text{keV} \tag{17}$$

Proton concentration at the time of nucleosynthesis in such a case:

$$n_p = \eta_B \frac{2\zeta(3)}{\pi^2} T_{NS}^3 \approx 4 \cdot 10^{18}\text{см}^{-3} \tag{18}$$

Let's evaluate the reaction rate of $n + p \to D + \gamma$.

$$\Gamma_{p(n\gamma)D} = n_p \cdot (\sigma v) \approx 0.24\text{c}^{-1}, \tag{19}$$

where $(\sigma v) \approx 6 \cdot 10^{-20} \frac{\text{см}^3}{c}$ is reaction cross section.

The resulting reaction rate is much higher than the expansion rate of the Universe at nucleosynthesis temperature.

$$H(T_{NS}) = \frac{1.66 T_{NS}^2 \sqrt{g_*}}{M_{\text{Pl}}} \approx 3.5 \cdot 10^{-3} c^{-1} \tag{20}$$

The concentration of free protons is determined by the expression:

$$n_p(t_{NS}) = n_p(0) \cdot e^{-n_n(\sigma v) t_{NS}}, \tag{21}$$

where $t_{NS} = \frac{1}{2H(T_{NS})} \approx 142c$

Let us finally determine the mass fraction of free protons that can form hydrogen atoms:

$$X_p = \frac{n_p(t_{NS})}{n_p(0) + n_n} = \frac{e^{-n_n(\sigma v) t_{NS}}}{1 + \frac{n_n}{n_p(0)}} \tag{22}$$

Substituting the numerical values, we obtain the upper and lower estimates of the mass fraction of free protons: $10^{-22} < X_p < 10^{-15}$.

4 Mirror structures formation

From the estimates of nucleosynthesis results, it follows that stars composed of neutrons and helium will form within the framework of this model. In such stars, helium combustion reactions and the subsequent capture of α-particles will produce $N\alpha$ elements. Further combustion reactions of these elements may produce nuclei that differ in their nucleon composition from those of the normal world.

Let us estimate the possibility of β-decays of some nuclei. Weizsäcker's semiempirical formula for the binding energy of a nucleus:

$$E_{\mathrm{b}} = \alpha A - \beta A^{\frac{2}{3}} - \gamma Z^2 A^{-\frac{1}{3}} - \delta(A-2Z)^2 A^{-1} + \xi A^{-\frac{1}{2}}, \tag{23}$$

where α = 15.67 MeV, β = 17.21 MeV, γ = 0.75 MeV, δ = 93.2 MeV, ξ for even-even nuclei = 12 MeV, ξ for odd-even = -12 MeV, ξ for odd-even = 0.

β^+-decay $(A, Z) \to (A, Z-1) + e^+ + \nu$ is energetically advantageous if the following condition is obtained:

$$M_{(A,Z)} - M_{(A,Z-1)} > 2m_e \tag{24}$$

$$m_p - m_n - E_{\mathrm{b}(A,Z)} + E_{\mathrm{b}(A,Z-1)} > 2m_e \tag{25}$$

Taking the upper bound of the proton-neutron mass difference $m_p - m_n \approx m_e$, we obtain the condition for the possibility of β^+-decay:

$$\gamma(2Z-1)A^{-\frac{1}{3}} + 4\delta(2Z-A-1)A^{-1} - 2\xi A^{-\frac{1}{2}} > m_e \tag{26}$$

Similarly for β^--decay:

$$-\gamma(2Z+1)A^{-\frac{1}{3}} + 4\delta(A-2Z-1)A^{-1} - 2\xi A^{-\frac{1}{2}} > 3m_e \tag{27}$$

Using these expressions, we can conclude that nuclei with a significant excess of nucleons can experience β-decay. Within the framework of this model, the calculation predicts β-radioactivity of all isotopes of carbon except ^{12}C and ^{13}C, for nitrogen except ^{14}N and ^{15}N.

Isotopes of the heavier element, uranium, were also considered. It turned out that under this model both ^{235}U and ^{238}U, as in the ordinary world, experience β^--decays, but do not experience β^+.

5 Dark Matter

Candidates for the dark matter (DM) in the framework of the considered model will be mirror baryons. To explain all the hidden mass, we can make the assumption that the density of mirror baryons will be 5 times the density of ordinary baryons. In this case, we can describe the mechanisms of mirror DM formation and make appropriate estimates.

Based on the estimates of mass fractions made in the section on nucleosynthesis, mirror neutrons and mirror helium will make the main contribution to the DM.

The mirror neutron gas will interact with the helium nuclei by the strong interaction. Here we need to estimate the interaction rates of mirror neutrons among themselves and neutrons with helium nuclei. It is necessary to check the energy and momentum transfer in collisions of neutrons with helium. If the energy and momentum transfer rate is greater than the expansion rate of the Universe, an equilibrium is established.

Mirror helium will also behave like a gas. At the recombination temperature of mirror helium, neutral He atoms will form, which will not be affected by radiation pressure forces. Once mirror helium becomes neutral, only mirror neutrons and mirror helium atoms remain. This detaches the nonrelativistic component from the mirror radiation and begins to play the role of a DM with the scale of structure determined by the momentum of helium recombination.

6 Conclusion

In this paper we considered a mirror world model with a ratio of nucleon masses $m_p - m_e < m_n < m_p$. The following properties of the mirror world were established:

- Mirror neutrons and protons are stable particles.
- There is an excess of mirror neutrons over mirror protons. Range of acceptable values of the ratio of the number of neutrons to the number of protons:

$$1 < \frac{n_n}{n_p} < 1.65$$

- The primary chemical composition of mirror matter is neutrons and helium nuclei with the following mass fractions:

$$0.75 < X_{He} < 1$$

$$0 < X_n < 0.25$$

- At the temperature of nucleosynthesis, the reaction rate $n + p \to D + \gamma$ significantly exceeds the expansion rate of the Universe, so the concentration of free protons is very low. The mass fraction of free protons is in the range:

$$10^{-22} < X_p < 10^{-15}$$

- stars are formed consisting of neutrons and helium. In such stars, helium combustion reactions and the subsequent capture of α-particles give rise to $N\alpha$elements. Further combustion reactions of these elements can produce nuclei that differ in their nucleon composition from those of the normal world.
- Mirror nuclei with a significant excess of nucleons can experience β-decays.

References

1. *Lee T. D.*, *Yang C. N.* Question of Parity Conservation in Weak Interactions // Phys. Rev. — 1956. — Oct. — Vol. 104, issue 1. — P. 254–258.

2. *Wu C. S.* [et al.]. Experimental Test of Parity Conservation in Beta Decay // Phys. Rev. — 1957. — Feb. — Vol. 105, issue 4. — P. 1413–1415.

3. *Christenson J.* [et al.]. Evidence for the 2π decay of the K_2^0 meson // Phys. Rev. — 1964. — July. — Vol. 13. — P. 138–140.

4. *Okun L. B.* On a search for mirror particles // preprint ITEP. — 1983. — Vol. 149.

5. *Зельдович Я.*, *Хлопов М.* Масса нейтрино в физике элементарных частиц и космологии ранней Вселенной // УФН. — 1981. — Vol. 135. — P. 45–77.

6. *Хлопов М. Ю.* Основы космомикрофизики. — 2011.

7. *Linde A.* Chaotic inflation // Physics Letters B. — 1983. — Vol. 129, no. 3. — P. 177–181. — ISSN 0370-2693.

8. *Дубрович В.*, *Хлопов М.* О доменной структуре теневой материи // Астрон. журн. — 1989. — Vol. 66. — P. 232.